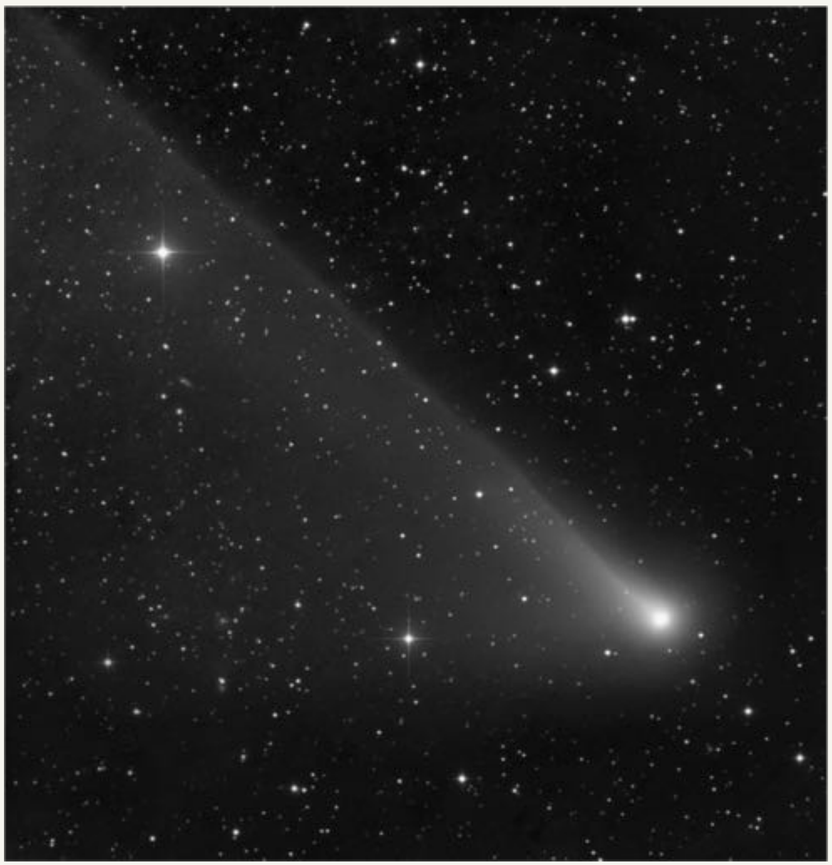
Comet C/2013 V5 (Oukaimeden): Evidence for Compositional Heterogeneity as Revealed through Infrared Spectroscopy

M. A. DiSanti (Code 693 and The Goddard Center for Astrobiology)



C/2013 V5 (Oukaimeden), 2014 Sep 14
(photo credit: D. Peach)

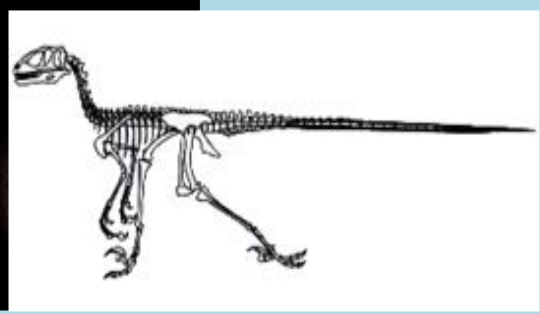
Collaborators/Team Members:

B. P. Bonev (American U.),
N. Dello Russo, R. J. Vervack (APL)
E. L. Gibb (U. Missouri-St. Louis),
N. X. Roth (UM-SL, grad student & PhD candidate),
A. J. McKay (USRA-NPP/GSFC),
H. Kawakita (Kyoto-Sangyo U.),
A. L. Cochran (U. Texas – McDonald Obs.)

Outline

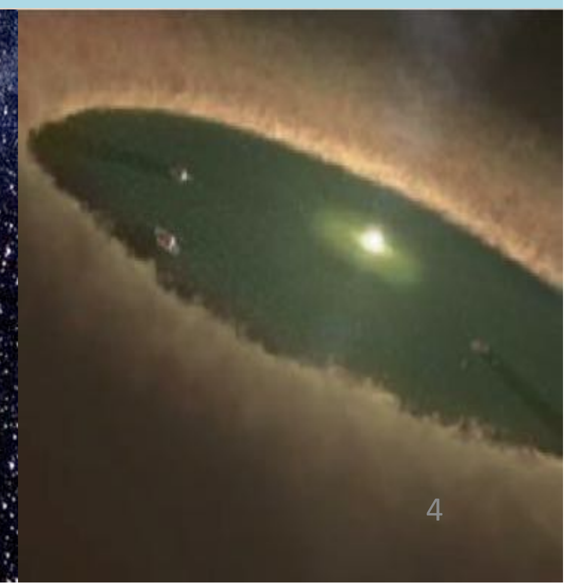
- Importance of and IR platforms for studies of cometary parent volatile composition
- Our study of C/2015 V5 (Oukaimaden); evidence for non-homogeneous composition in the nucleus
- Current/future capabilities: iSHELL at the IRTF

"Comets as Fossils"
Different types of fossils



Just as dinosaur fossils tell us about Earth at earlier times …

… comets tell us about our Solar System at earlier times



Carbon in comets

- **Refractory Organics (carbonaceous dust)**
  - Seen as continuum thermal emission, particularly at $\lambda \sim$ 3-5 µm for comets near heliocentric distance R_h = 1 AU
- **Volatile Organics**
  - Although H_2O is the dominant ice, comets also harbor a myriad of carbon-bearing ices, including PAHs
  - Upon sublimation cometary ices release parent volatiles (molecules) into the coma
  - The "simplest" (spectroscopically, structurally) of these are quantified using high resolution IR spectroscopy
- **The fraction of carbon in each reservoir (refractory, volatile) depends on a comet's gas-to-dust ratio, and carbon versus silicon content in grains**

Platforms (observatories + echelle spectrometers) available for near-IR (1-5 μm) spectroscopy at $\lambda/\Delta\lambda > 1 \times 10^4$

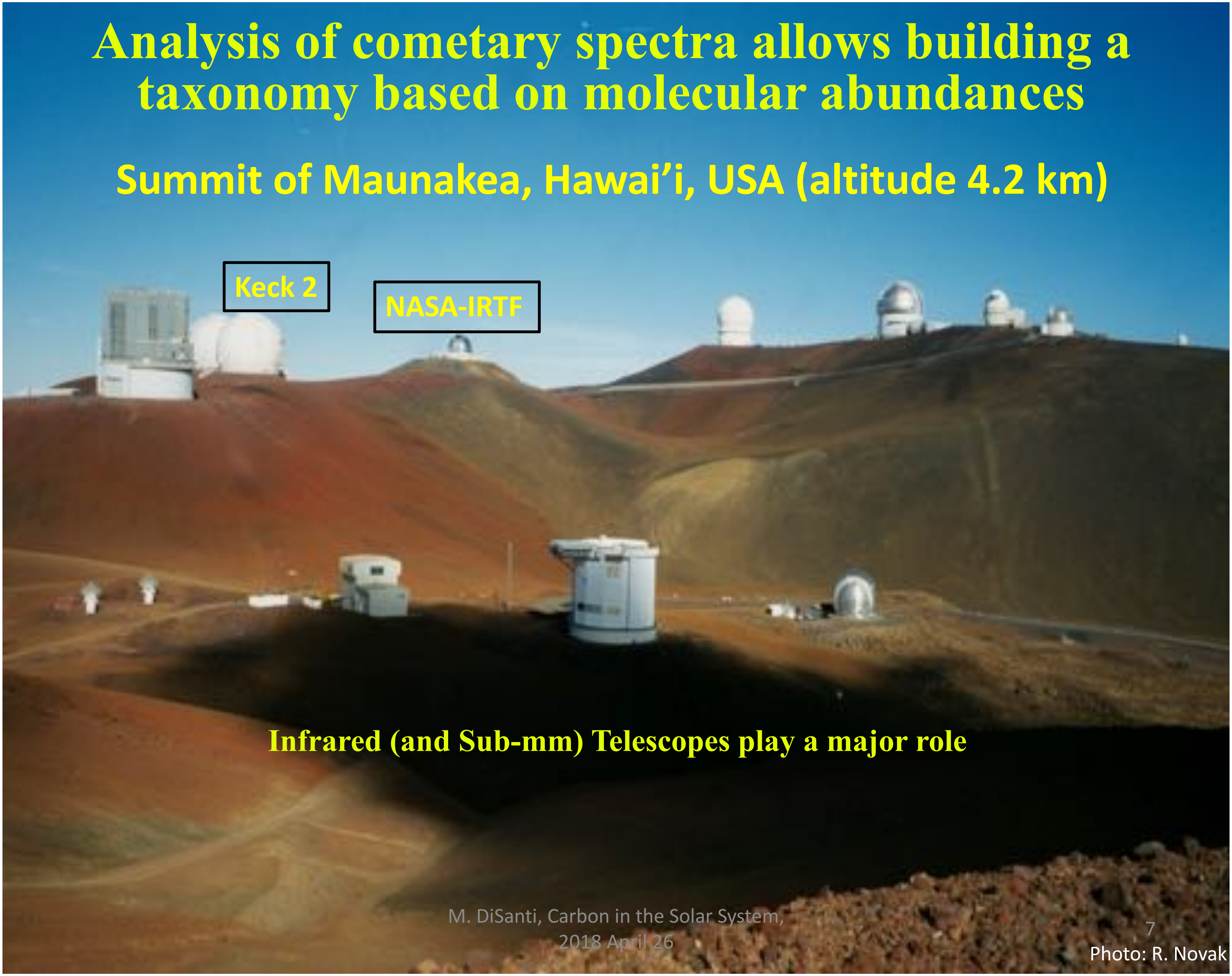
(used for our study of C/2013 V5 Oukaimeden)

- W. M. Keck (telescope 2): NIRSPEC
  - 10-m telescope, Maunakea Observatories (MKO), Hawai'i, USA
  - 1024x1024-pixels, 24 arc-sec slit length, multiple orders (cross-dispersed), $\lambda/\Delta\lambda \sim 2.5\times10^4$, piece-wise spectral coverage per setting
  - Scheduled upgrade begins Aug 1, back on Keck2 by Dec 9 (for 46P)

- NASA Infrared Telescope Facility (IRTF): CSHELL
  - 3-m telescope, MKO
  - 256x256-pixels, 30 arc-sec slit length, single echelle order, $\lambda/\Delta\lambda \sim 2.5\times10^4$, limited spectral coverage per setting
  - Daytime observing at IRTF – **unique capability among IR platforms**

Analysis of cometary spectra allows building a taxonomy based on molecular abundances

Summit of Maunakea, Hawai’i, USA (altitude 4.2 km)



Infrared (and Sub-mm) Telescopes play a major role

Photo: R. Novak

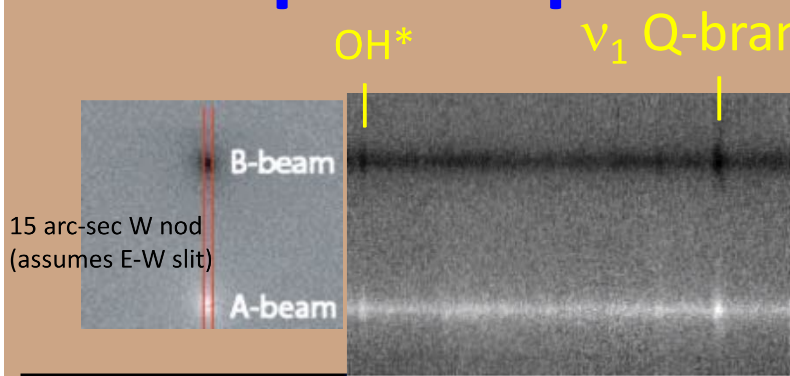
Compositional studies of cometary ices require high resolution spectroscopy ($\lambda/\Delta\lambda > 1 \times 10^4$)

The Near-IR (λ~1-5µm) affords key opportunities:

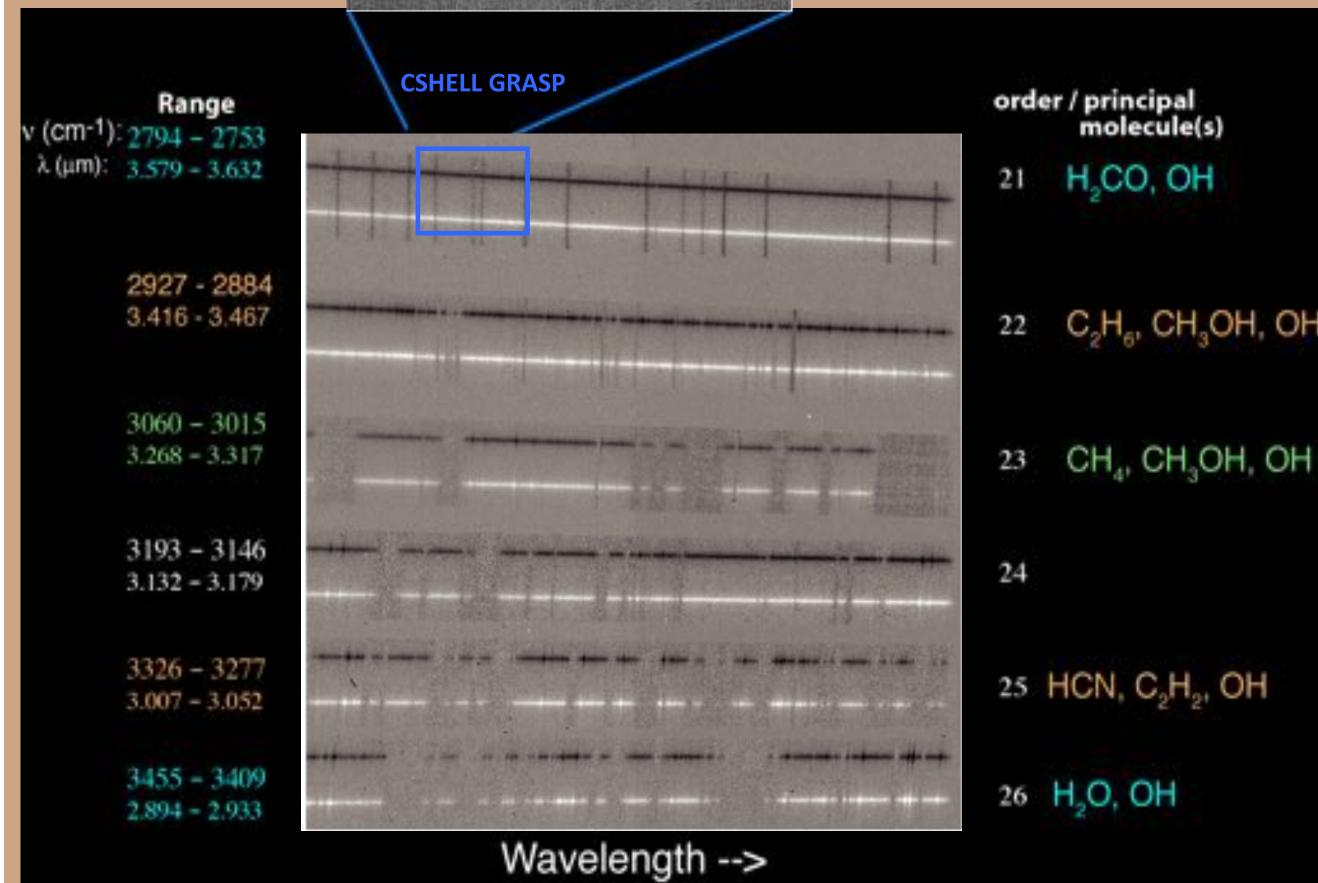
- Measurements of 7 - 10 "primary" (aka parent) volatiles **(H_2O, C_2H_2, CH_4, C_2H_6, CO, H_2CO, CH_3OH, HCN, NH_3, OCS)**
- Use of up-to-date HITRAN database to model telluric transmittances
- Direct detection of H_2O through non-resonant fluorescence
- OH Prompt emission (OH*): Proxy for H_2O abundance and spatial distribution
- Unique sounding of symmetric hydrocarbons (e.g., CH_4, C_2H_2, C_2H_6)
- Efficient measure of rotational temperatures (T_{rot})
- Spin temperatures (T_{spin}) for species w/ symmetric H-atoms (H_2O, CH_4, etc)
- Isotopic abundance ratios (HDO/H_2O, CH_3D/CH_4, etc.)
- Small (sub-arcsecond) pixels favor detection of primary volatiles (native ices; i.e., released directly from the nucleus)

= **Most relevant here**

Spatial-spectral frames: A - B differences



H_2CO in C/2002 T7 (LINEAR), UT 2002 May 05
(**CSHELL/IRTF**, **single order legacy instr.; "traditional" beam positions**)

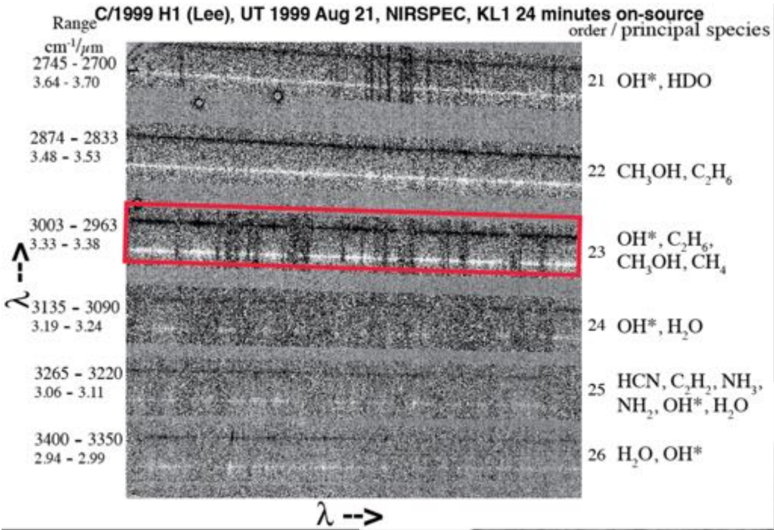


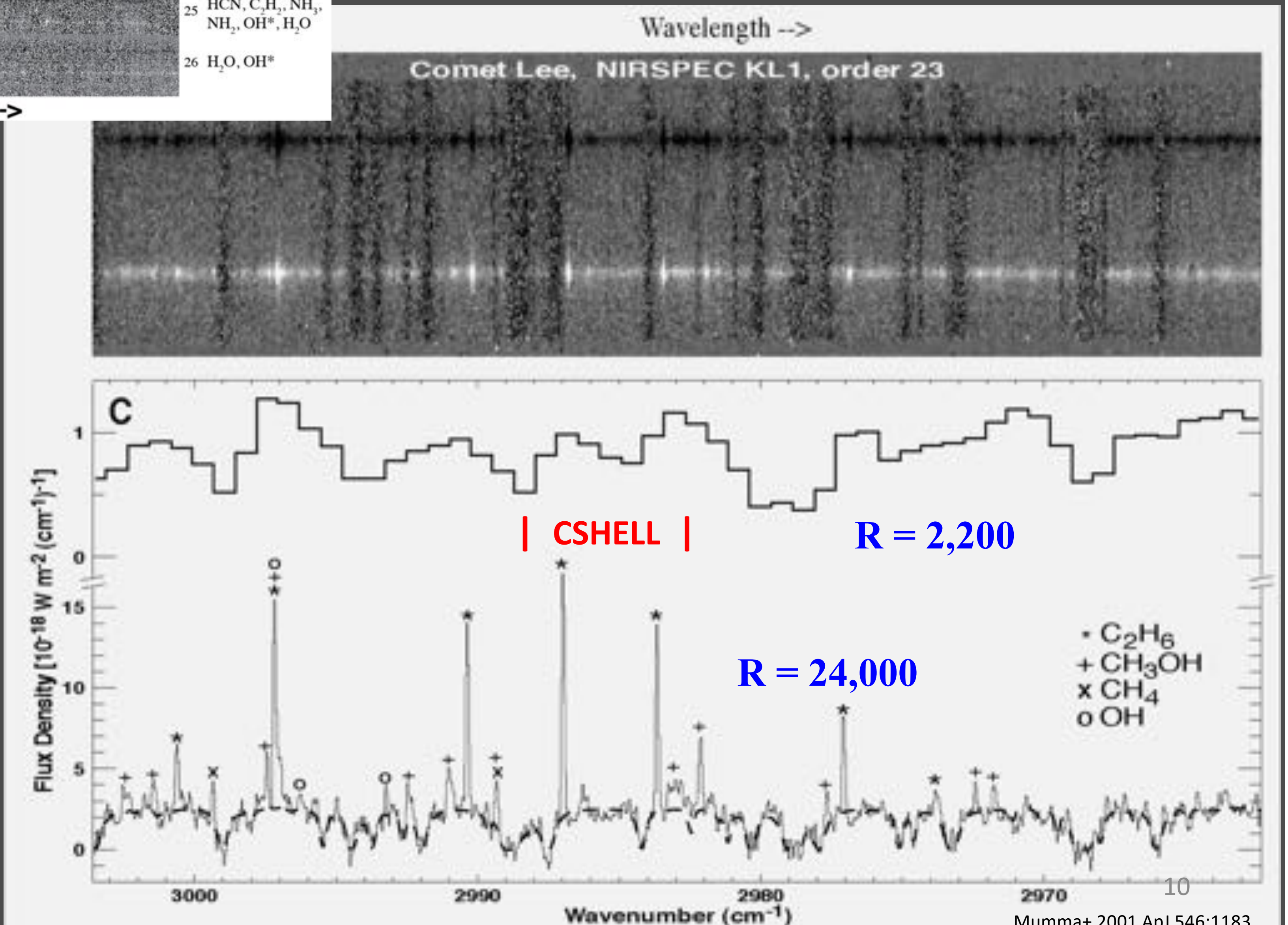
C/2004 Q2 (Machholz),
UT 2005 Jan 19
(**NIRSPEC/Keck**, **six orders**)

The Goddard Center for Astrobiology

High Spectral Resolution is Required

$\lambda/\Delta\lambda \geq 20{,}000$, versus $\sim 2{,}000$





Mumma+ 2001 ApJ 546:1183

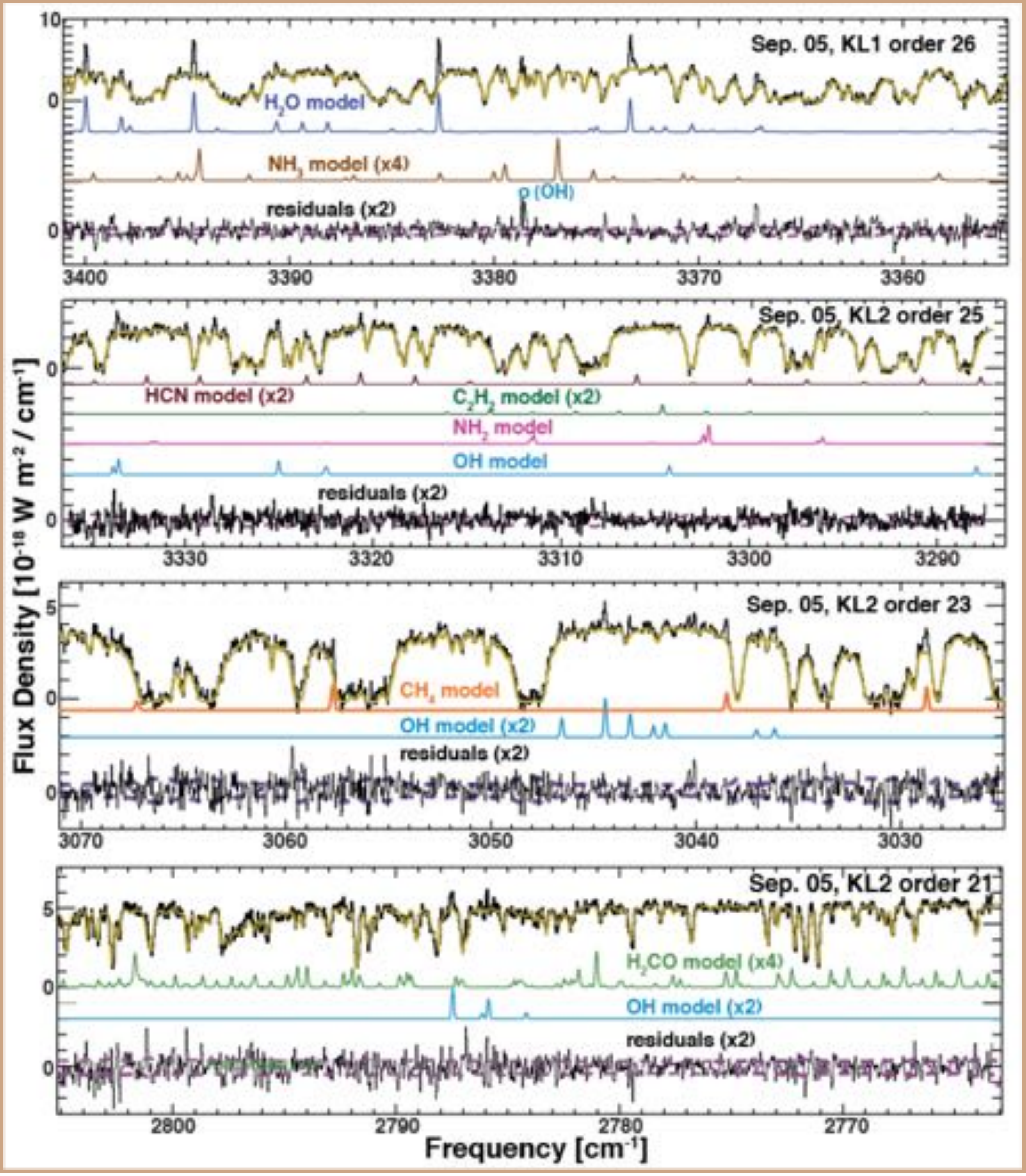
Our Compositional Study of Parent Volatiles/Native Ices in C/2013 V5 (Oukaimeden)

- Discovered 2013 Nov 12 (Oukaimeden Obs/Marrakech,Morocco); perihelion 2014 Sep 28; a_0 = 55000 AU so Oukaimeden is a dynamically new or at least extremely long-period comet from the Oort cloud

- NIRSPEC on UT 2014 Sept 5 – 6
  - Eight trace parent volatiles (C_2H_2, CH_4, C_2H_6, CO, H_2CO, CH_3OH, HCN, NH_3) were **measured simultaneously with H_2O**, using three instrument settings (KL1, KL2, MWA)
  - This simultaneity overcomes sources of systematic errors (e.g., slit loss correction, potential temporal variability in gas production & outflow)
  - Observations were limited to the last ~ 75 minutes of the night

- CSHELL on UT 2014 Sept 11 – 13
  - All observations were after sunrise so during daytime
  - Detections limited to two settings, simultaneously measuring CO & H_2O on all dates

Sample L-band Spectra of C/2015 V5 (NIRSPEC)



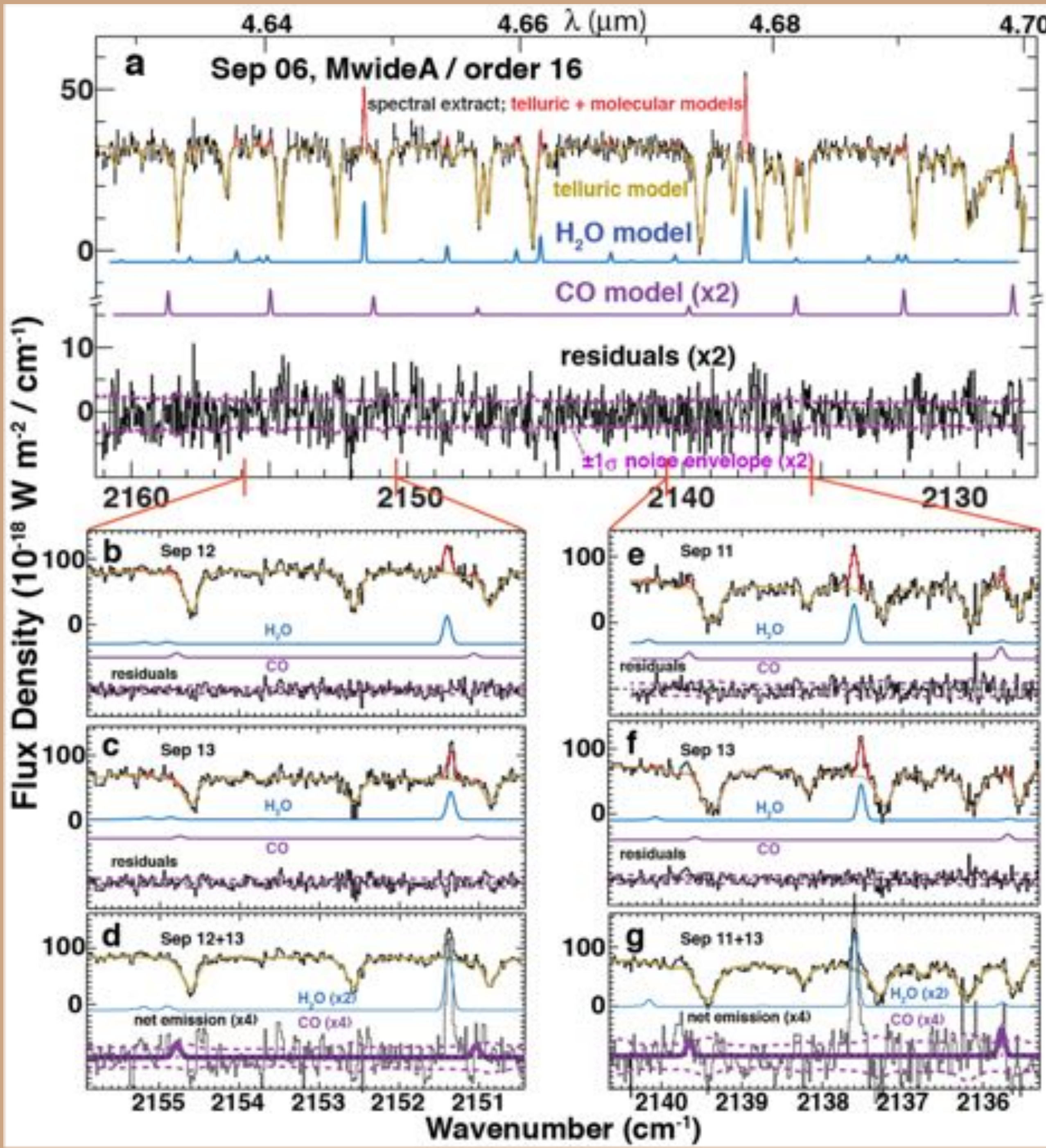
λ ≅ 2.94-2.98 μm

λ ≅ 3.00-3.04 μm

λ ≅ 3.26-3.31 μm

λ ≅ 3.57-3.62 μm

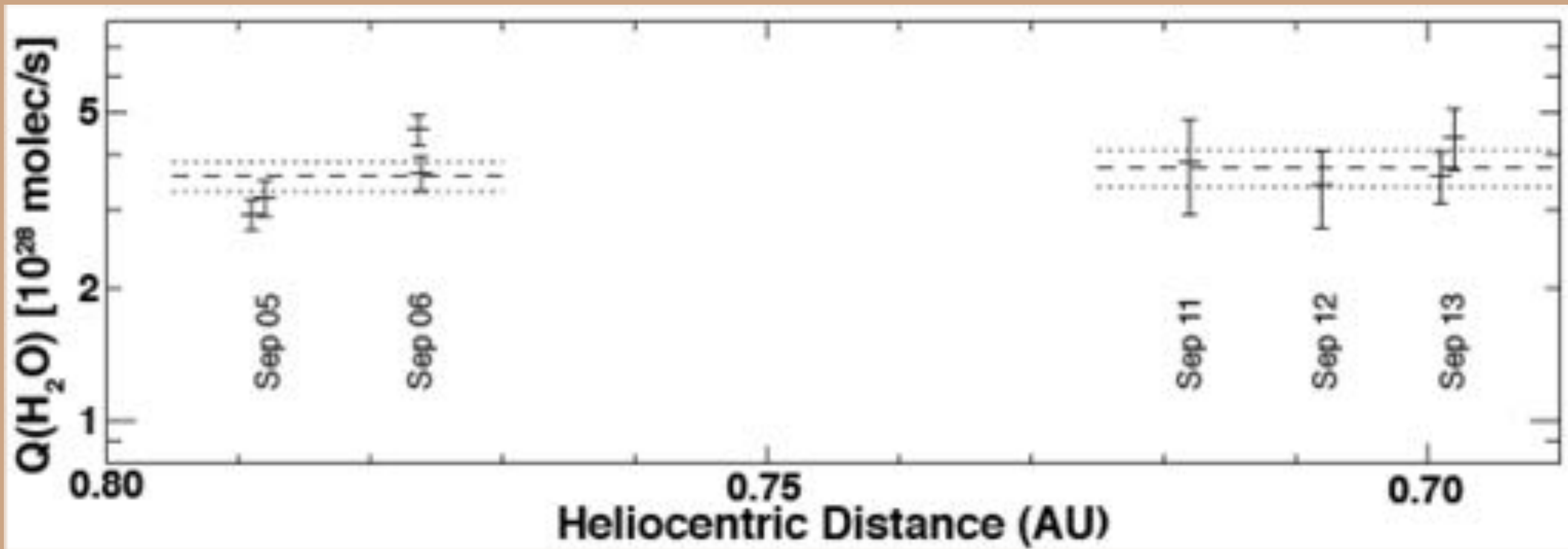
M-band Spectra (CO & H_2O)



NIRSPEC

CSHELL

H_2O Production in C/2015 V5



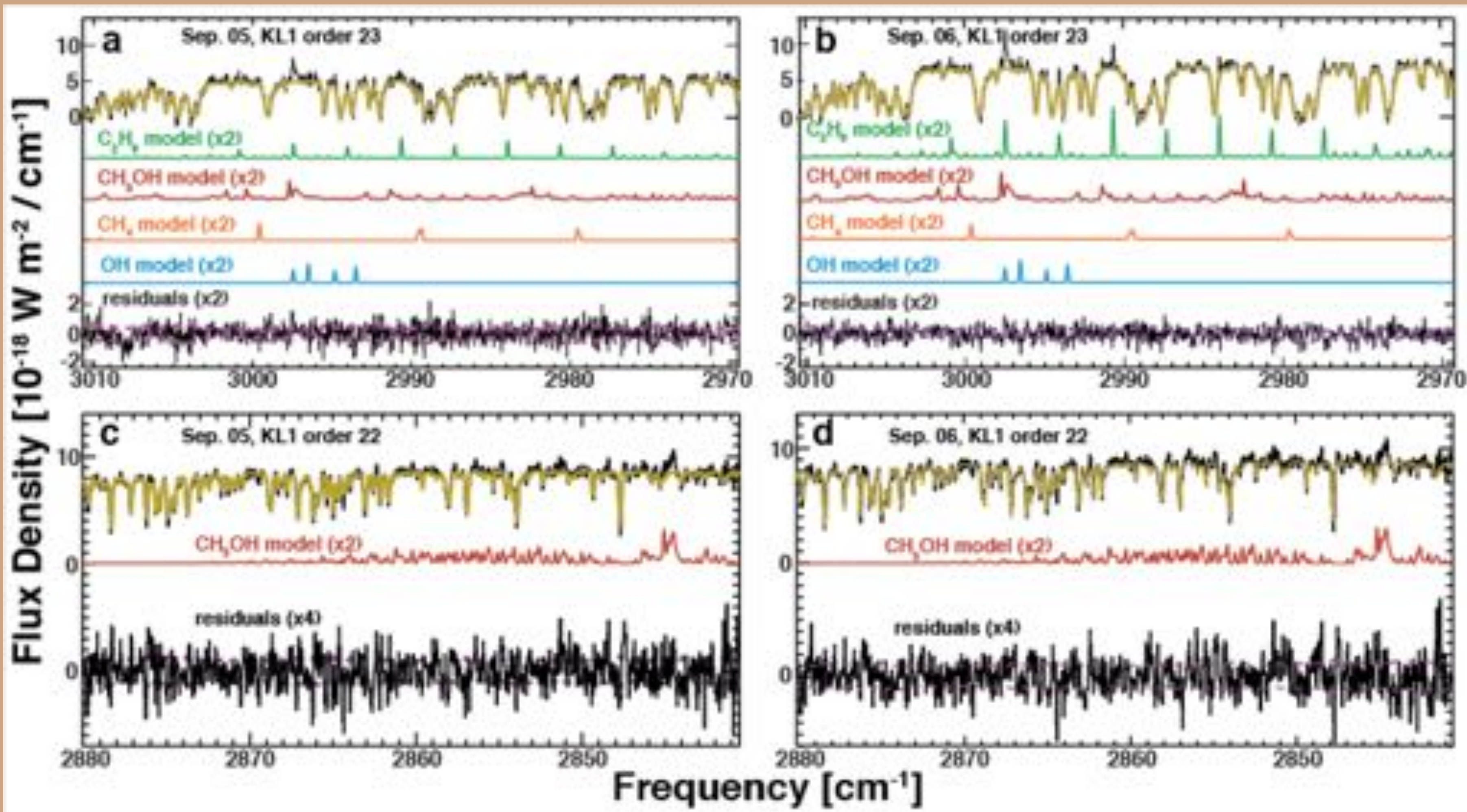
$Q(H_2O) \propto R_h^{-1.1+1.0}$ (relatively flat);
Slope and Q are consistent with SOHO/SWAN, w/ much larger FoV, between R_h = 1.1 and 0.625 AU (Combi+ 2018 Icar 300:33)

=> Relatively localized release of H_2O (from nucleus or innermost coma)

C/2013 V5: Evidence for Compositional heterogeneity

Sep 05 **Sep 06**

KL1 order 23: λ≅3.32 – 3.37 µm

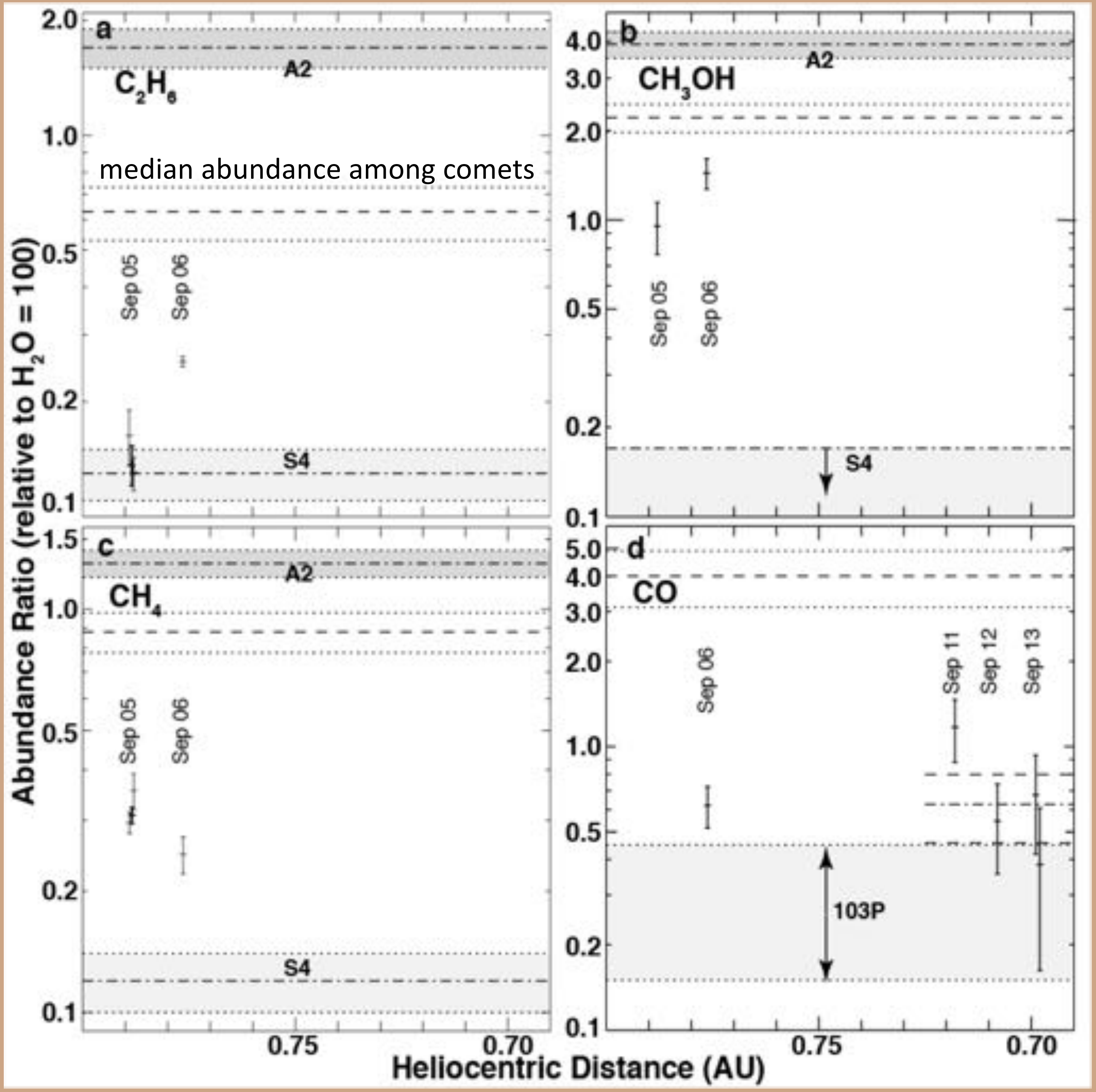


Sep 05 **Sep 06**

KL1 order 22: λ≅3.47 – 3.52 µm

Note: Much stronger C_2H_6 and moderately stronger CH_3OH on Sep 06

Compositional heterogeneity (cont'd)

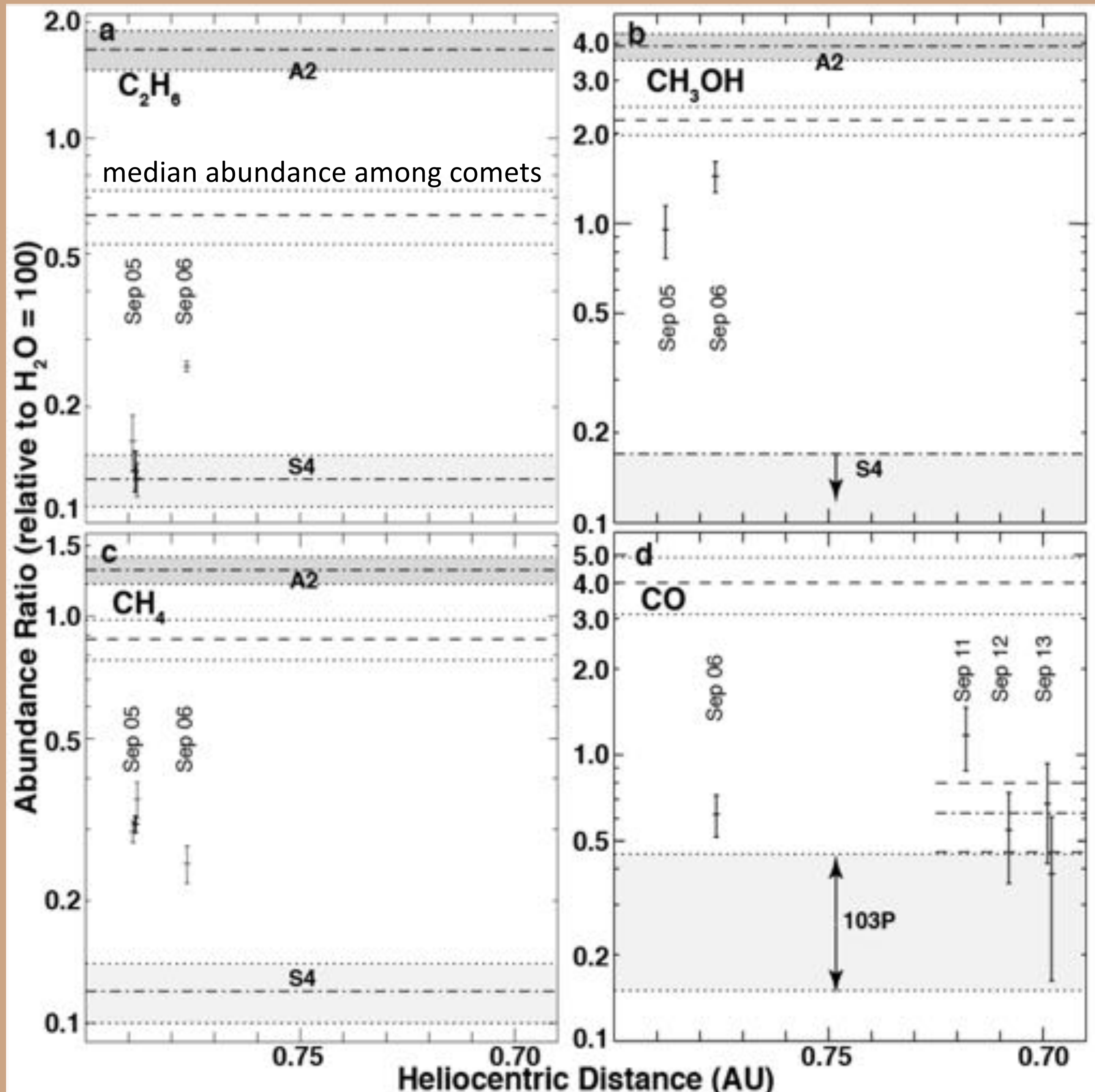


Compositional heterogeneity (cont'd)

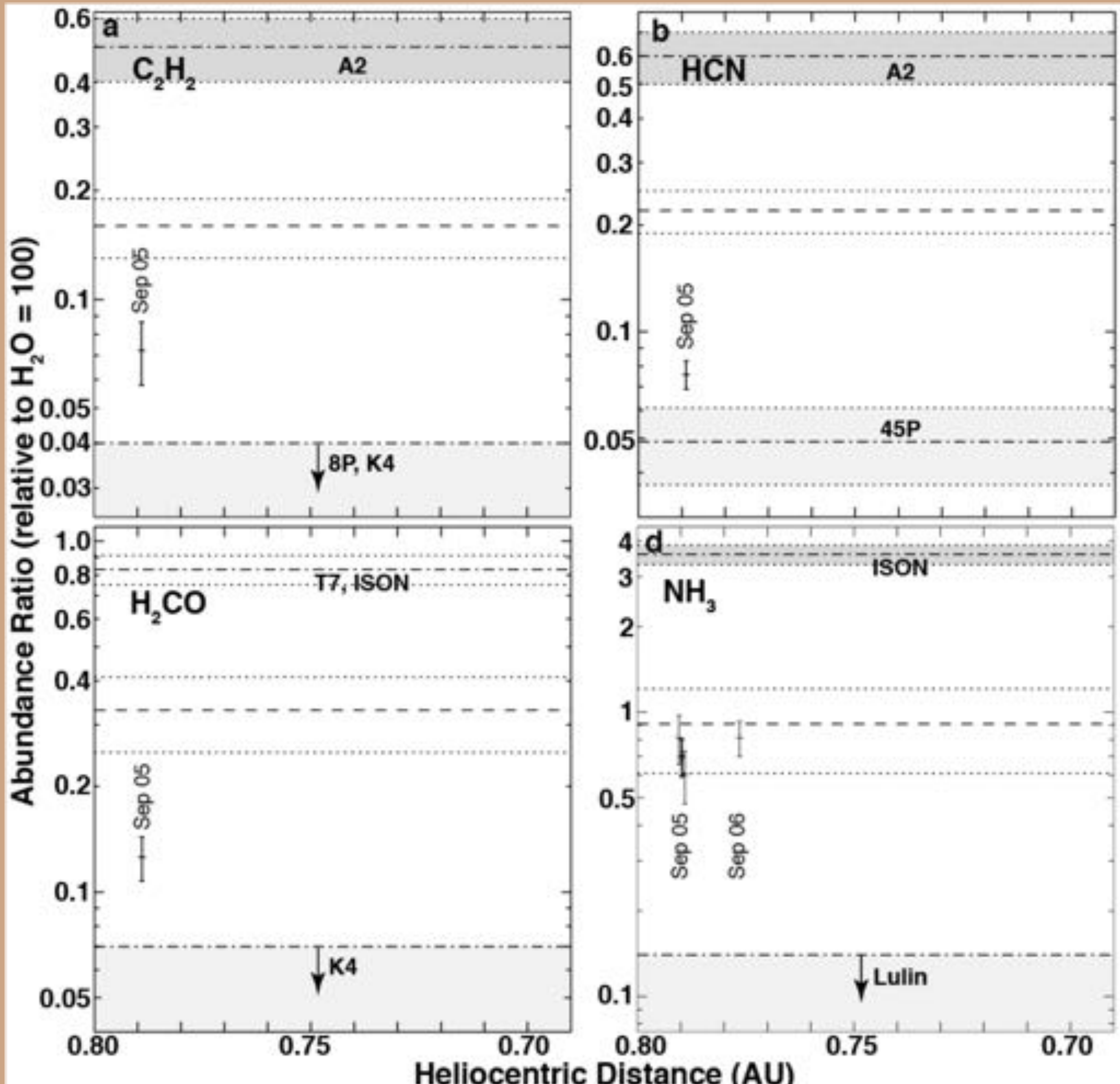
<u>Sep 06 versus Sep 05</u>

CH_3OH/H_2O higher by 51 ± 35 %

C_2H_6/H_2O was higher by 87 ± 23 %



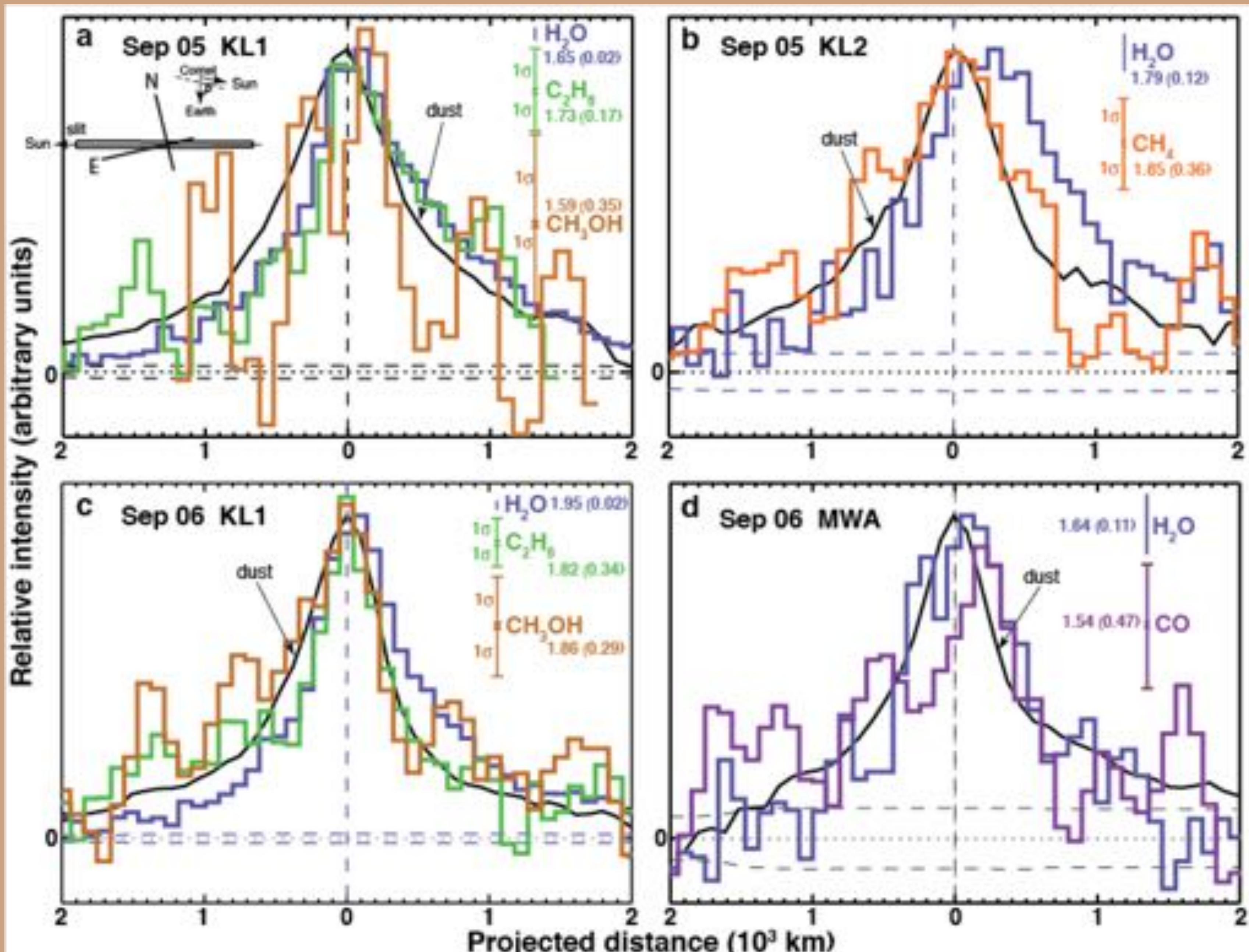
Additional "Snapshots" of Abundances in C/2015 V5



Spatial Profiles of H_2O, organics, and dust

C_2H_6 follows H_2O

C_2H_6 differs from H_2O



Summary of Results for C/2013 V5 (Oukaimeden)

- H_2O production was fairly flat between ~ 0.8 and 0.7 AU pre-perihelion. Agreement with SOHO/SWAN all-sky observations of the Ly-α coma.
  - $Q(H_2O)$ was larger by 42 ± 15 % on Sep 06 compared with Sep 05

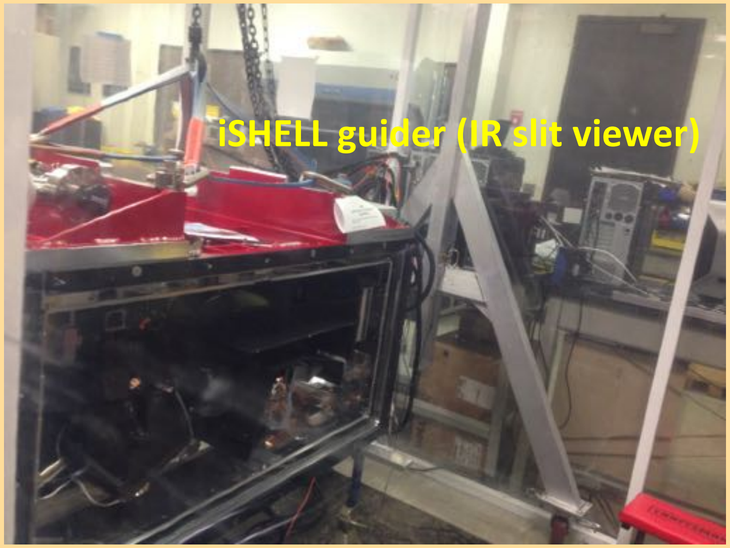
- Overall, parent volatiles were depleted compared with their median values among comets. Exception: NH_3 was "normal"

- C_2H_6 was severely depleted on Sep 05 & tracked H_2O spatial profile => association w/ "polar" (H-bonded) ice?; less depleted on Sep 06, spatially distinct from H_2O => C_2H_6 was sequestered in a distinct (a-polar) phase of ice(?)
  - $Q(CH_3OH)$ increased by 1.9 ± 0.2 (by 51 ± 35% wrt H_2O)
  - $Q(C_2H_6)$ increased by 2.7 ± 0.3 (!!) (by 87 ± 23% wrt H_2O)

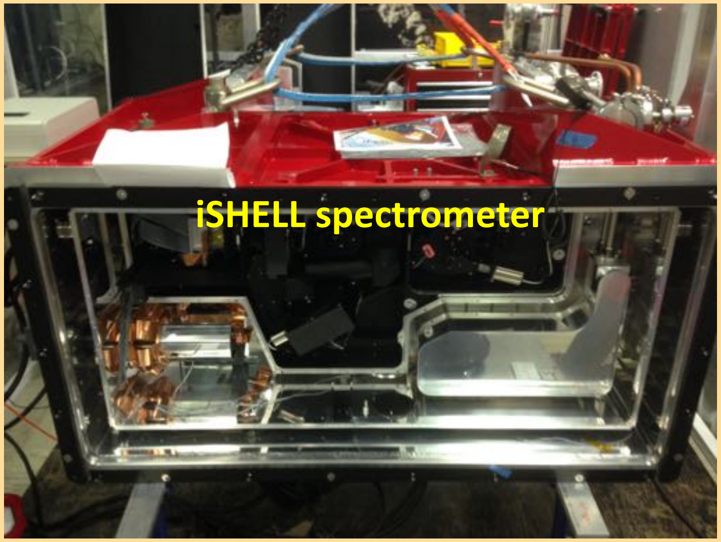
- Implications for interstellar [H-atom addition to C_2H_2 ($\rightarrow C_2H_6$), CO ($\rightarrow CH_3OH$) on grains] versus nebular (gas-phase) chemistry
  - Compositional studies have since become more addressable…our study of C/2013 V5 would definitively have been more complete if we'd had….

Current/Future IR Observational Prospects

- NIRSPEC upgrade (pending)
  - Install a modern 2K x 2K H2RG detector array, retain cross-dispersed capability
- New spectrograph at the IRTF (iSHELL) (Rayner et al. 2016 SPIE 9908:1) / CSHELL replacement beginning October 2016
  - 2K x 2K array detector, cross-dispersed; has IR slit-viewer (fr. SpeX)
  - Daytime observing capability w/ $\lambda/\Delta\lambda$ up to ~ 70,000 (~ 40,000 matches 0.7" seeing)
  - Serial coverage of comets to small heliocentric distances => addresses observational biasing associated with measurements at a single R_h
  - Six comets measured in 2017A semester, one (so far) in 2018A, five more comets targeted for 2018B, ending with 46P/Wirtanen (dedicated campaign time at IRTF)



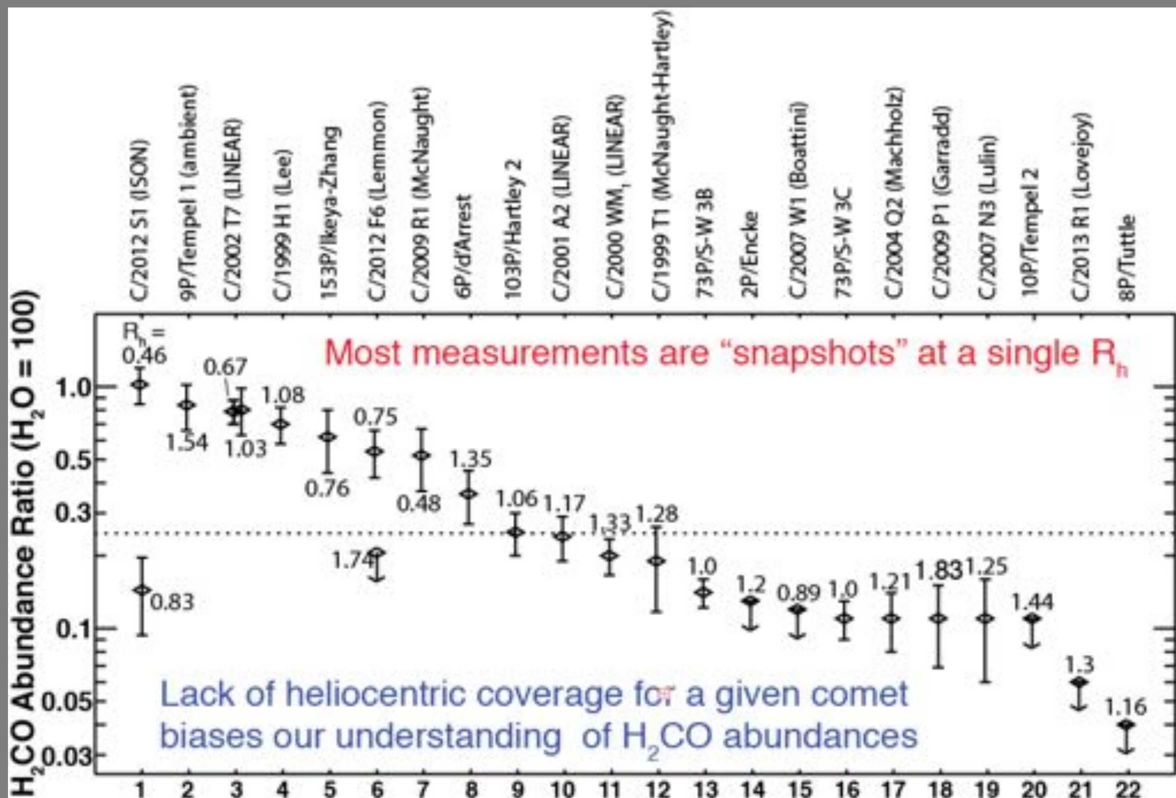
iSHELL: ala SpeX, but w/ much higher $\lambda/\Delta\lambda$!



iSHELL at IfA/Manoa, Aug. 2015

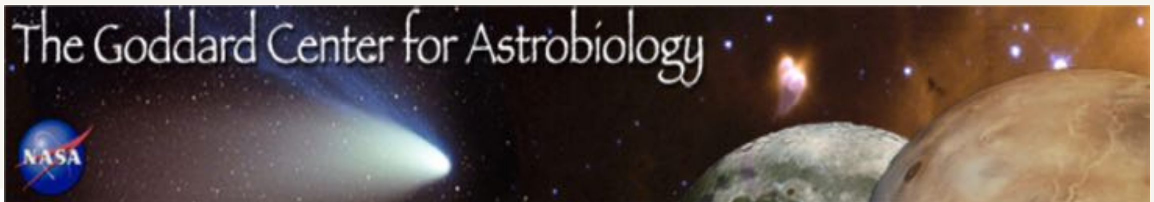
Bridging toward the future: The need for serial measurements of comets (aka over a range of heliocentric distances, R_h)

Most compositional studies are "snapshots" (single R_h, or over a very limited range in R_h)
e.g., H_2CO offers a case in point…this introduces a **bias** when interpreting compositions



There are relatively few measurements at multiple R_h. Comet ISON in particular provided a unique opportunity for serial measurements! **However**, do observed changes in abundances of some species (especially H_2CO, NH_3, HCN) suggest compositional heterogeneity, or is release from increasingly heated (ice- or refractory-dominated) grains important? **iSHELL will enable serial studies of comets to small R_h!**

Acknowledgements



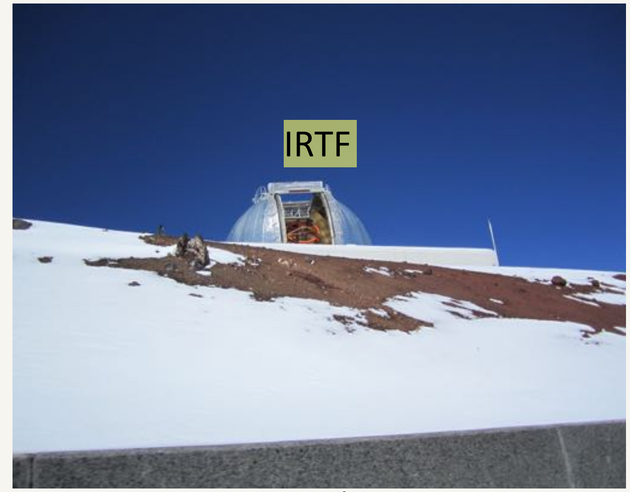
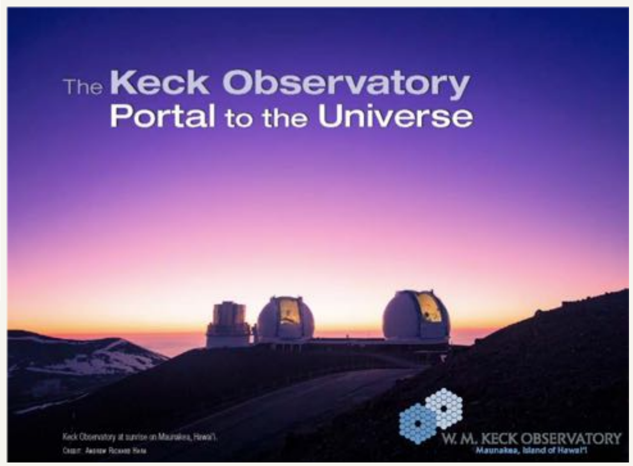


Photo: K. Fast (NASA/HQ), Feb. 24, 2013



Thanks to: The NASA Planetary Astronomy/Solar System Observations Programs, the NASA Planetary Atmospheres/Solar System Workings Programs, the NASA Astrobiology Institute, the National Science Foundation